

Concrete Dam Foundation Risks

Best Practices in Dam and Levee Safety Risk Analysis
Part D – Embankments and Foundations
Chapter D-7

Last modified June 2017, presented July 2018



US Army Corps
of Engineers®



Outline

- Objectives and key concepts
- Historical perspective
- Case studies
- Foundation discontinuities and potential failure modes
- Discontinuity shear strength
- Foundation uplift pressures and forces
- Foundation modulus and loading considerations
- Multi-block systems
- Exercise (important to complete this)



Objectives

- Understand the mechanisms that affect concrete dam foundation failure
- Understand how to construct an event tree to represent concrete dam foundation failure (exercise)
- Understand how to estimate the probability of concrete dam breach due to foundation failure (exercise)



Key Concepts

- Foundation deficiencies are the number one cause of concrete dam failures
- The location, orientation, and strength (including scale effects) of discontinuities often control the stability of concrete dams on rock
- Kinematic analyses can be used to evaluate concrete dam foundation stability – often 3-D analyses are needed (even for gravity dams)
- The effects of uplift pressures and drainage must be considered
- Loading from the dam and dam-foundation interaction must be considered
- Internal erosion of soil foundations under concrete dams not covered here – see section on Internal Erosion



Concrete Dam Failures, after ICOLD 1995+

Failure Type	Concrete Dams
Overtopping	5 (9%)
Foundation*	29 (53%)
Uplift	4 (7%)
Materials	5 (9%)
Structural	6 (11%)
Spillway	5 (9%)
Seismic Deformation**	1 (2%)
Total	55

*Includes Camara Dam, 2004

**Shi Kang Dam, 1999 Chi Chi Taiwan E.Q.



Case Studies

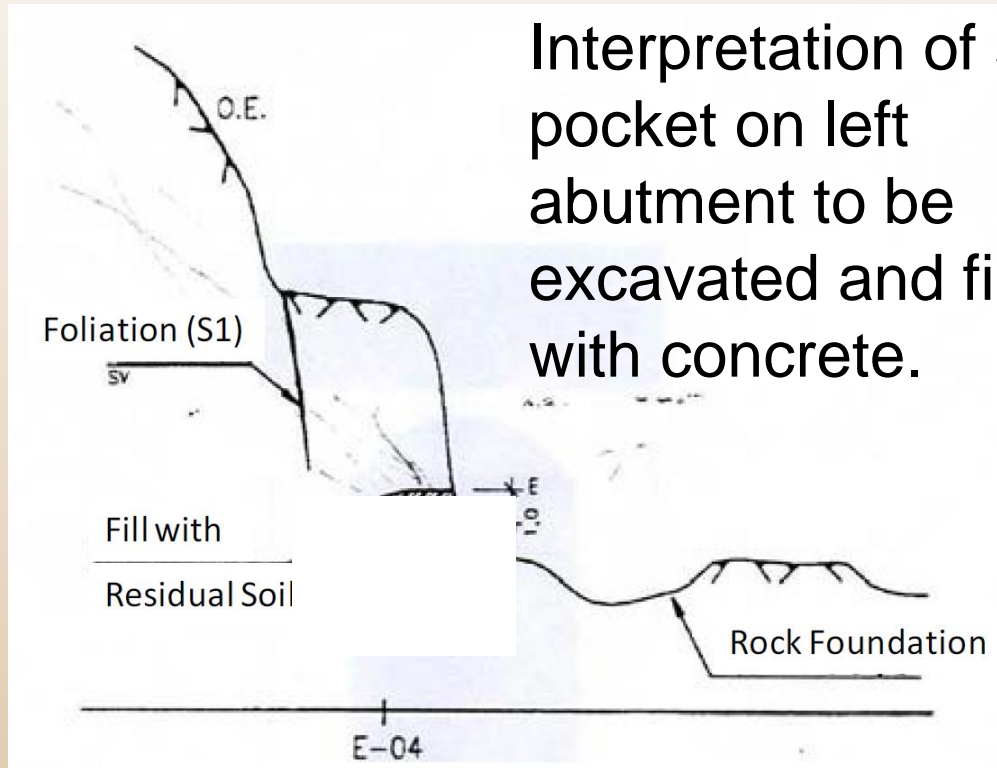


Camara Dam, Brazil



- Originally designed as an embankment dam
- Switched to 160-ft-high RCC gravity dam after majority of explorations were completed
- Additional explorations for RCC dam were not adequate
- Gallery through dam for grout and drainage curtain

Camara Dam, Brazil



Interpretation of soil pocket on left abutment to be excavated and filled with concrete.



Dam foundation gneissic migmatites with foliation dipping 30 to 35 degrees toward the right abutment.

Camara Dam, Brazil

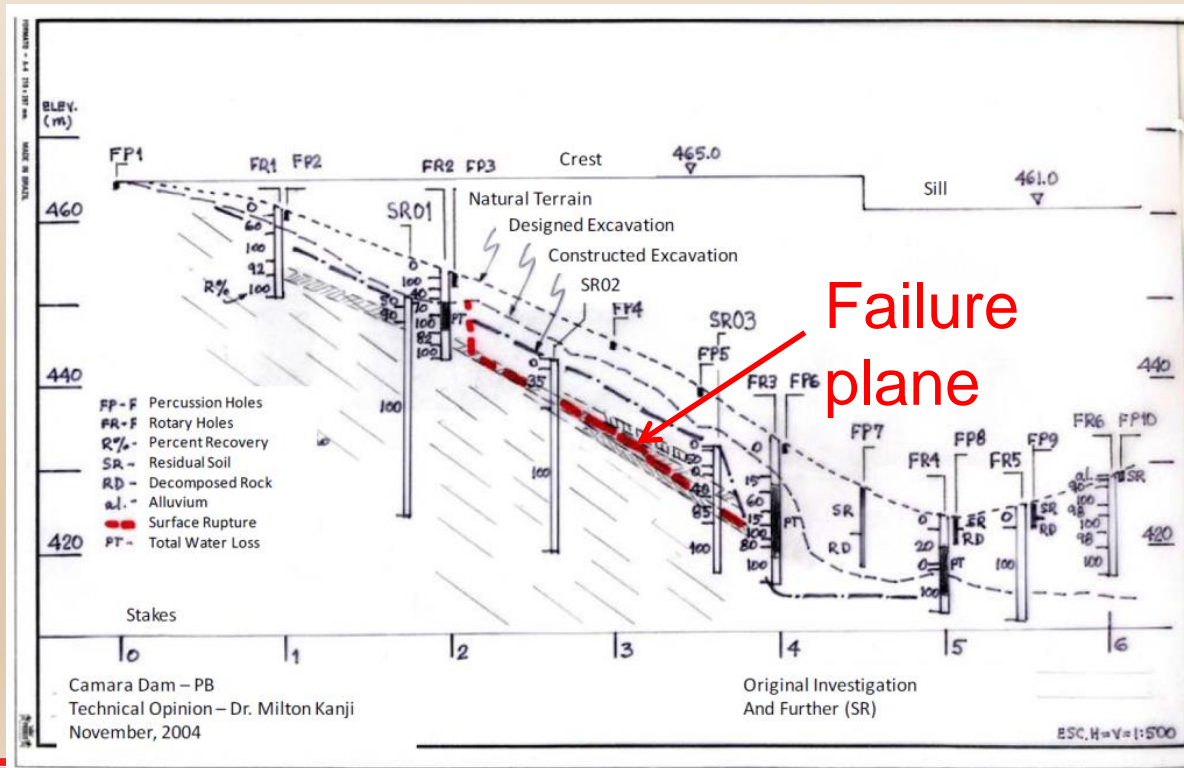
- Reservoir filled to within 5 m of full pool quickly in early 2004 due to heavy rains
- Filling continued into June 2004
- Reports of **material carried by drain flows, plugged drains**, and wet spot d/s toe left abutment during this time period
- Dam failed June 17, 2004
- 5 deaths
- 800 homeless



Note that dam bridged over failure zone

Camara Dam, Brazil

Arrow points to remnant of shear zone
Note unfractured footwall
Note direction of sliding toward channel



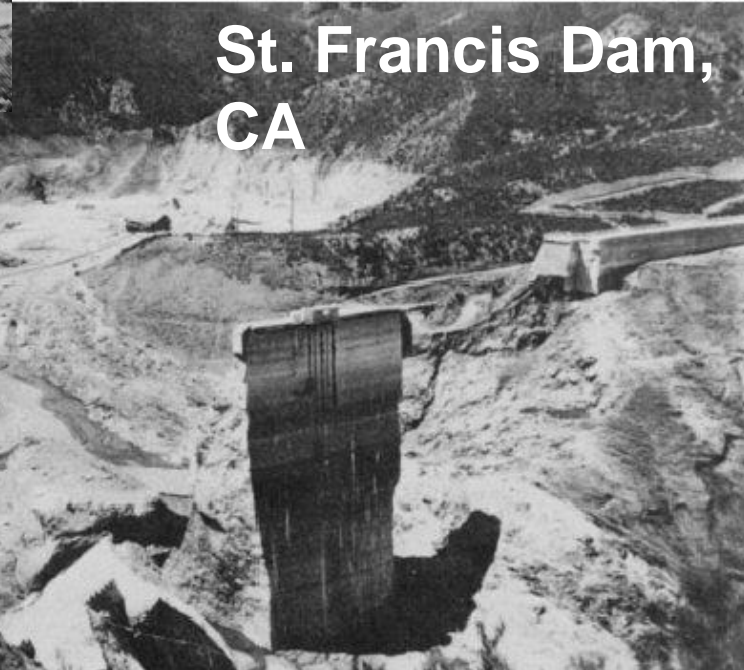
- (1) Large uplift pressures in shear zone caused block to slide, or
- (2) Erosion of shear left a gap into which dam collapsed

Profile developed post-failure

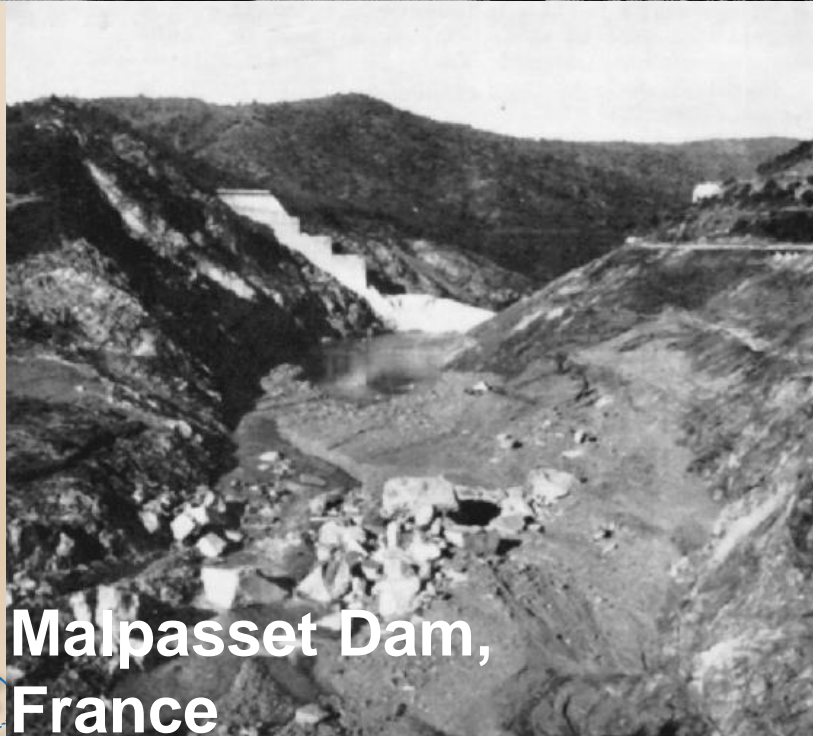
Other Notable Foundation Failures



Austin Dam, PA



St. Francis Dam,
CA



Malpasset Dam,
France

Discontinuities and Potential Failure Modes



Foundation Stability Analysis

Identify potential sliding failure modes

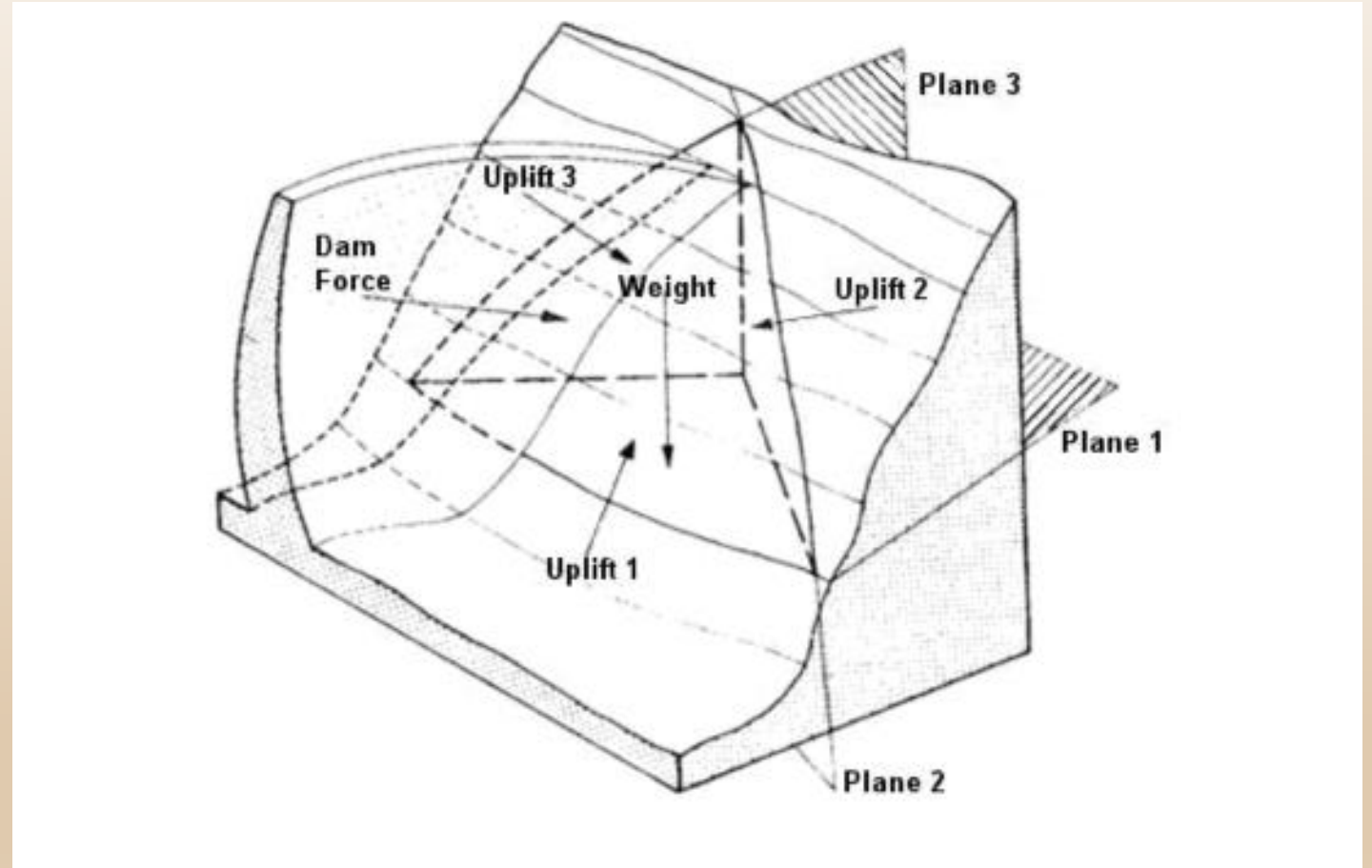
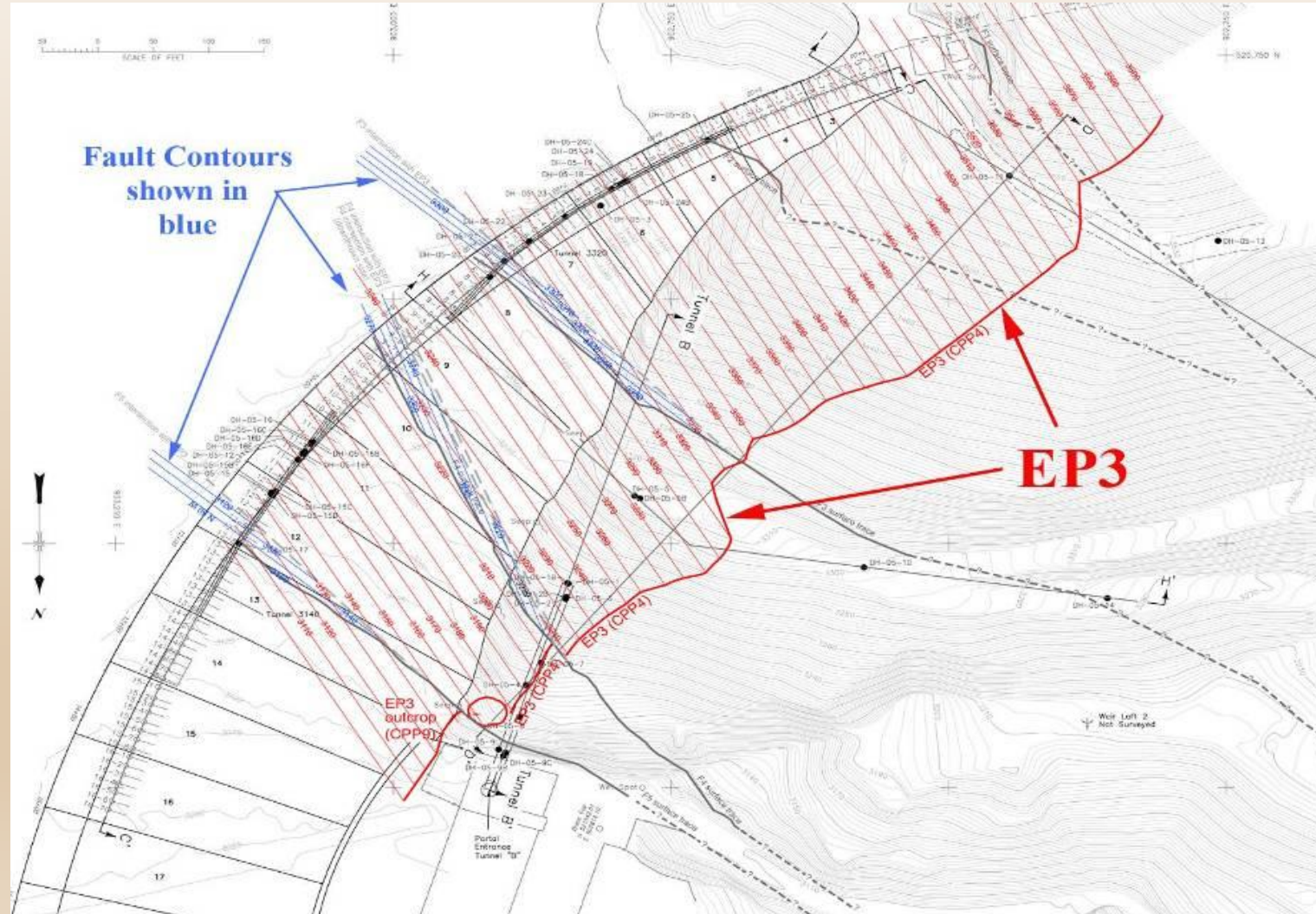


Figure 16. Rock Block within the Foundation of an Arch Dam. Plane 1, Plane 2, and Plane 3 are Discontinuity Planes; Uplift 1, Uplift 2, and Uplift 3 are Water Forces; W is the Block Weight; and Dam Force is the Thrust from the Dam (adapted from Londe [22]).

Structural Contours for Major Bedding Plane Partings and Faults

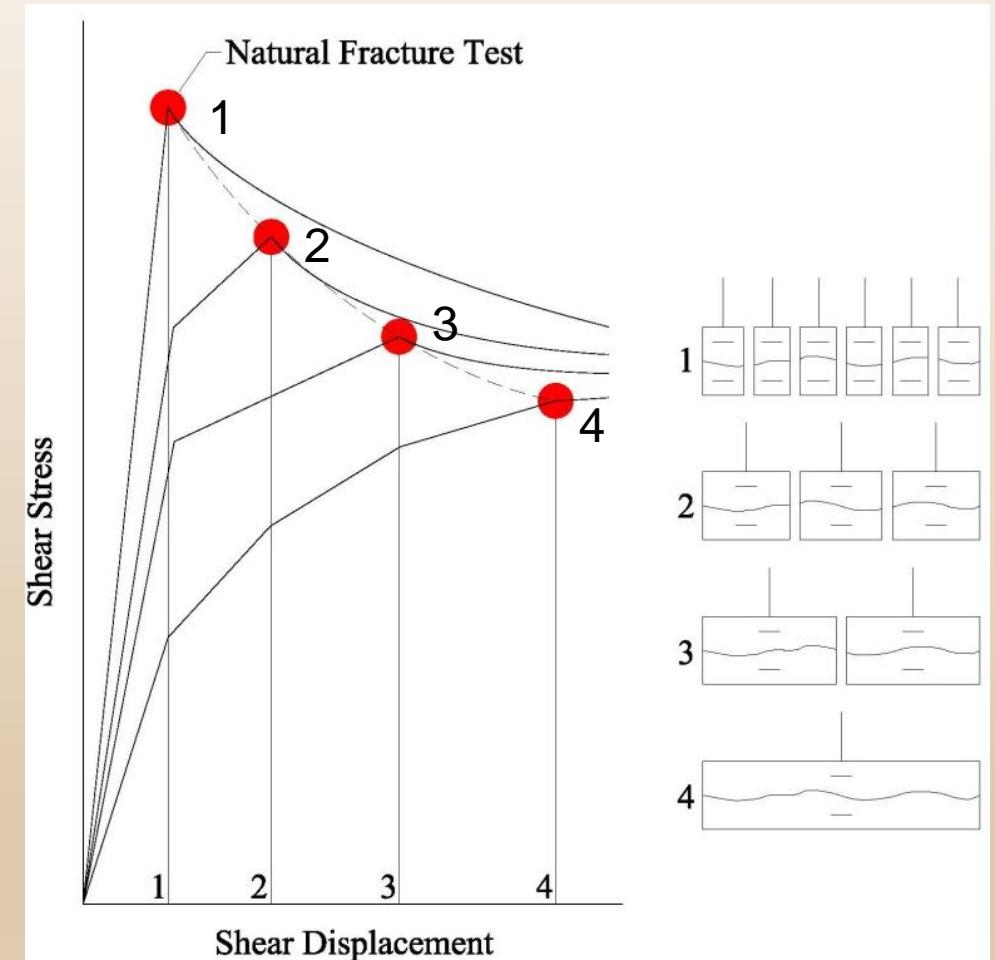


Construction Photos are Invaluable



Discontinuity Strength – Scale Effects

- Small scale rough samples overestimate strength
- Saw cuts typically under-estimate basic friction angle
- Test actual joints and subtract roughness (dilation angle) by measuring horizontal and vertical displacements) to obtain basic friction angle
- Add in large scale field roughness measured from outcrops
- See manual for details

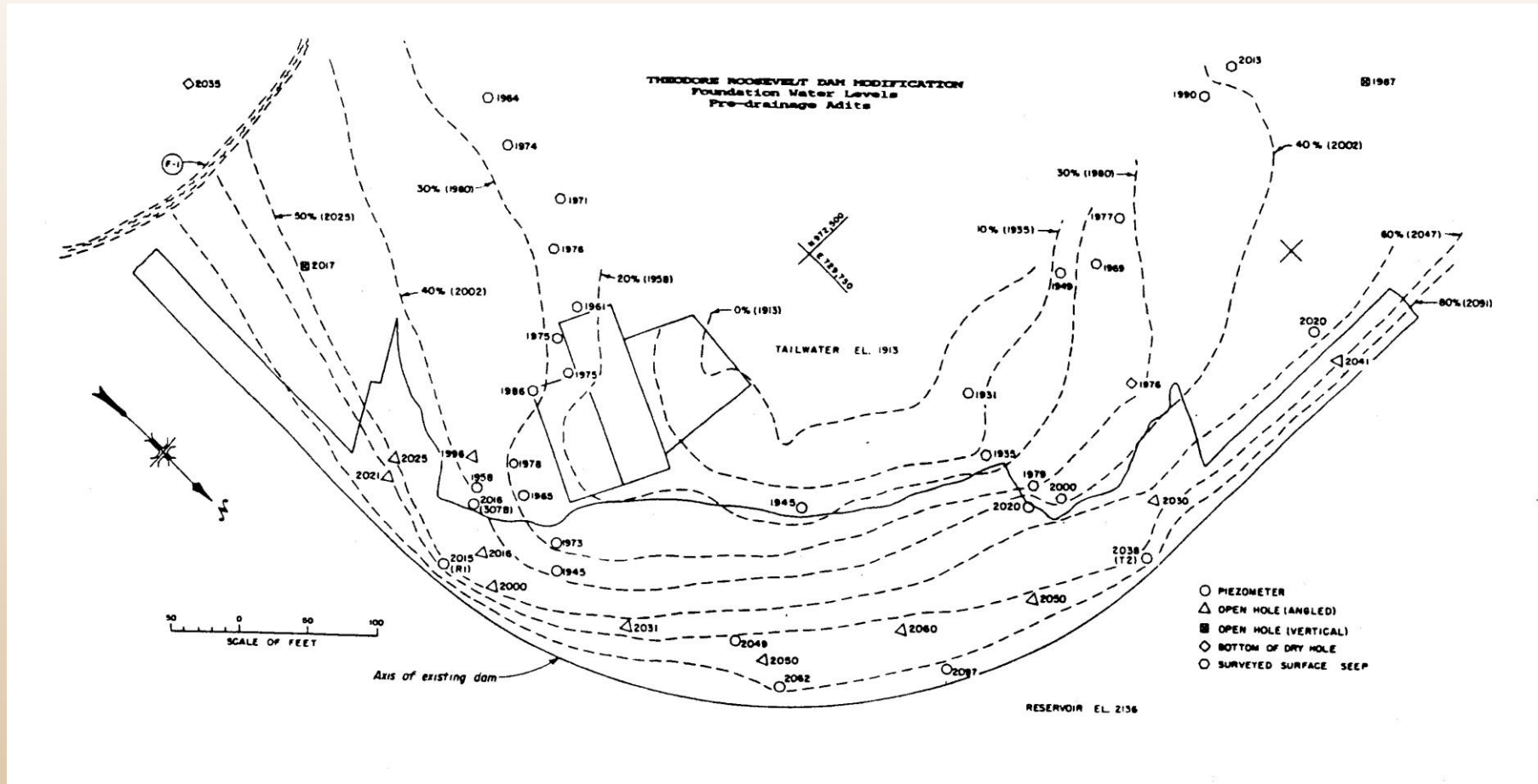


Adapted from Bandis et al (1983)

Foundation Uplift Pressures



Foundation Water Pressures



$$DHR = \frac{\text{Piezometric El} - \text{Tailwater El}}{\text{Reservoir El} - \text{Tailwater El}}$$

Used to estimate @ other RWS Elevations



Effects of Foundation Drains

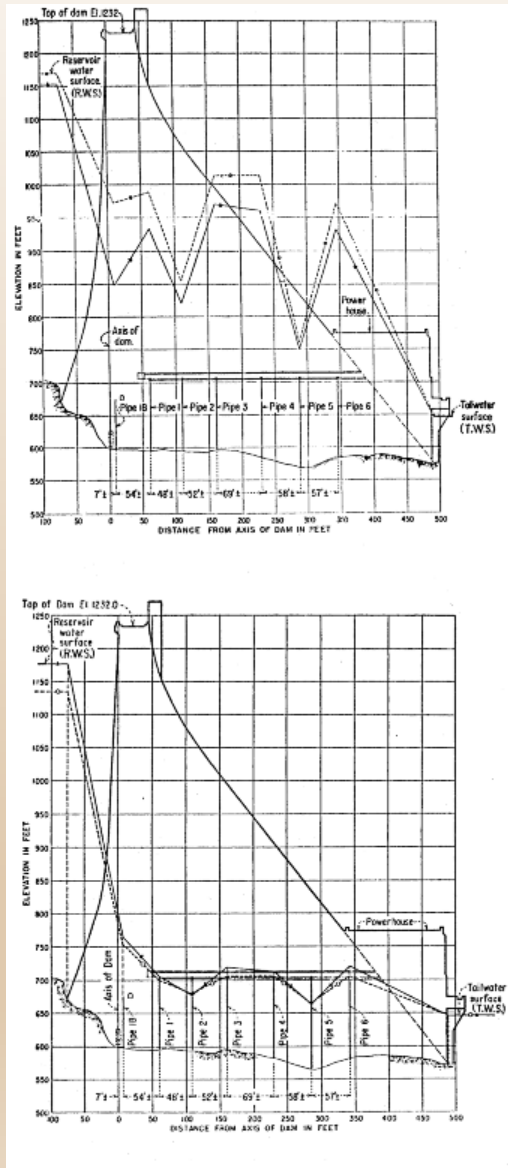


Figure C3. Uplift Measurements at Hoover Dam.
Note: 1 ft = 0.3048 m.

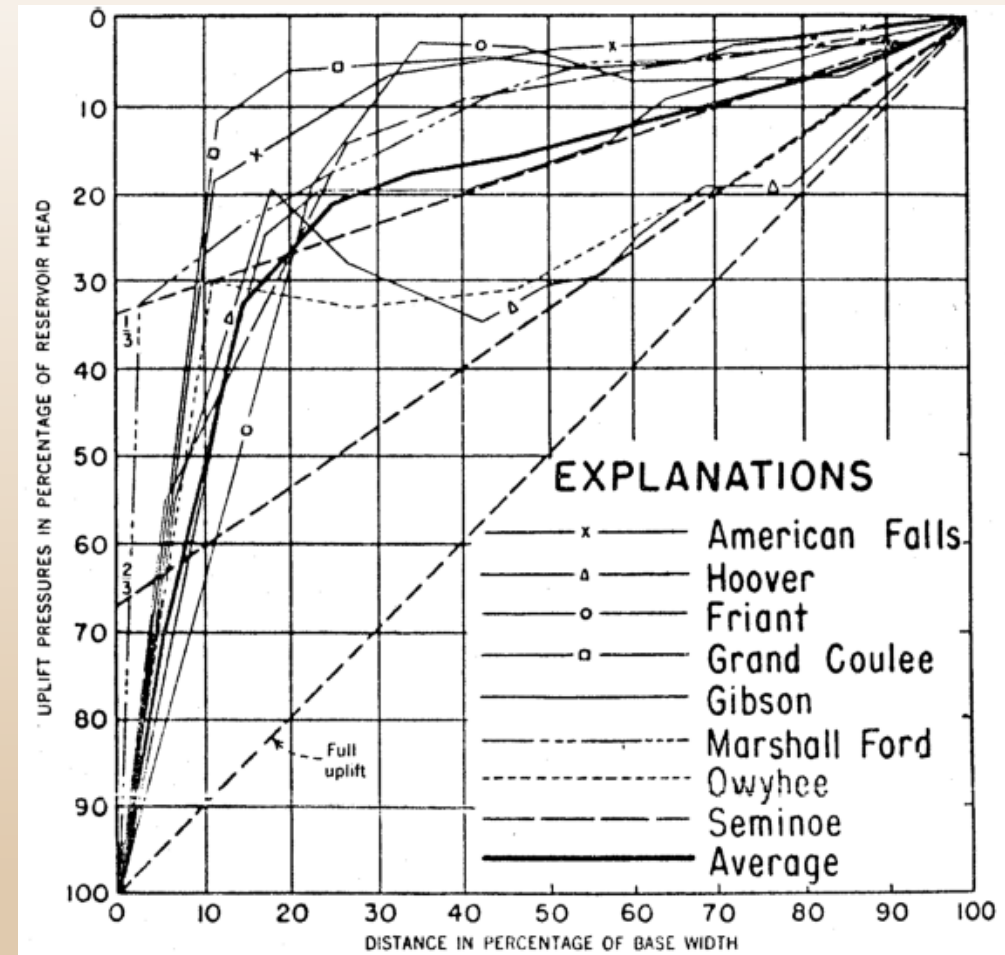
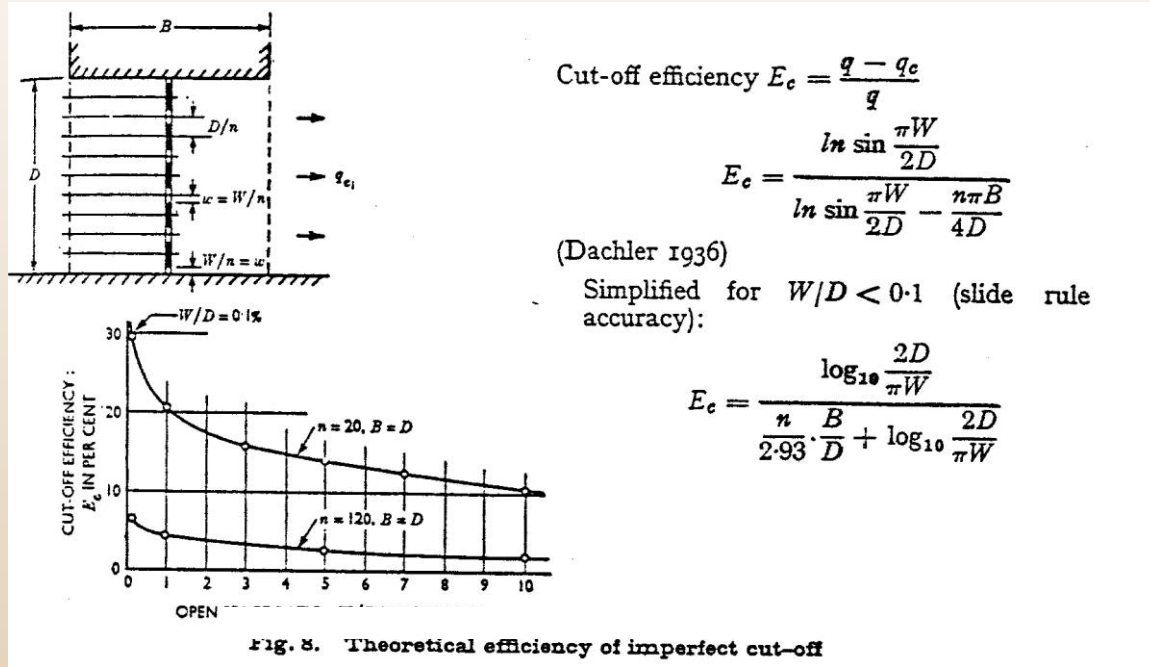


Figure C2. Uplift Measurements Recorded at Reclamation Concrete Dams

Drain depth (into fdn.) should be about 40% of hydraulic height, drains must be cleaned and maintained.

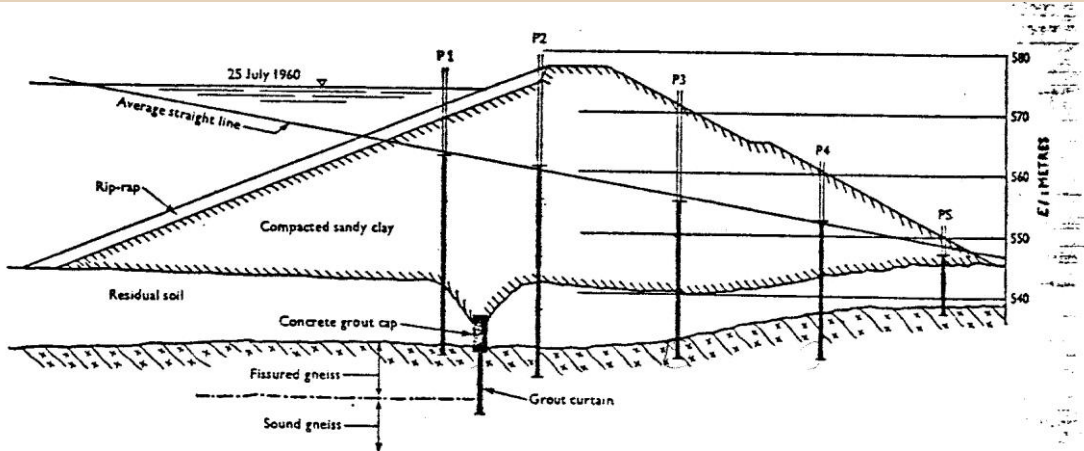
Grout Effectiveness



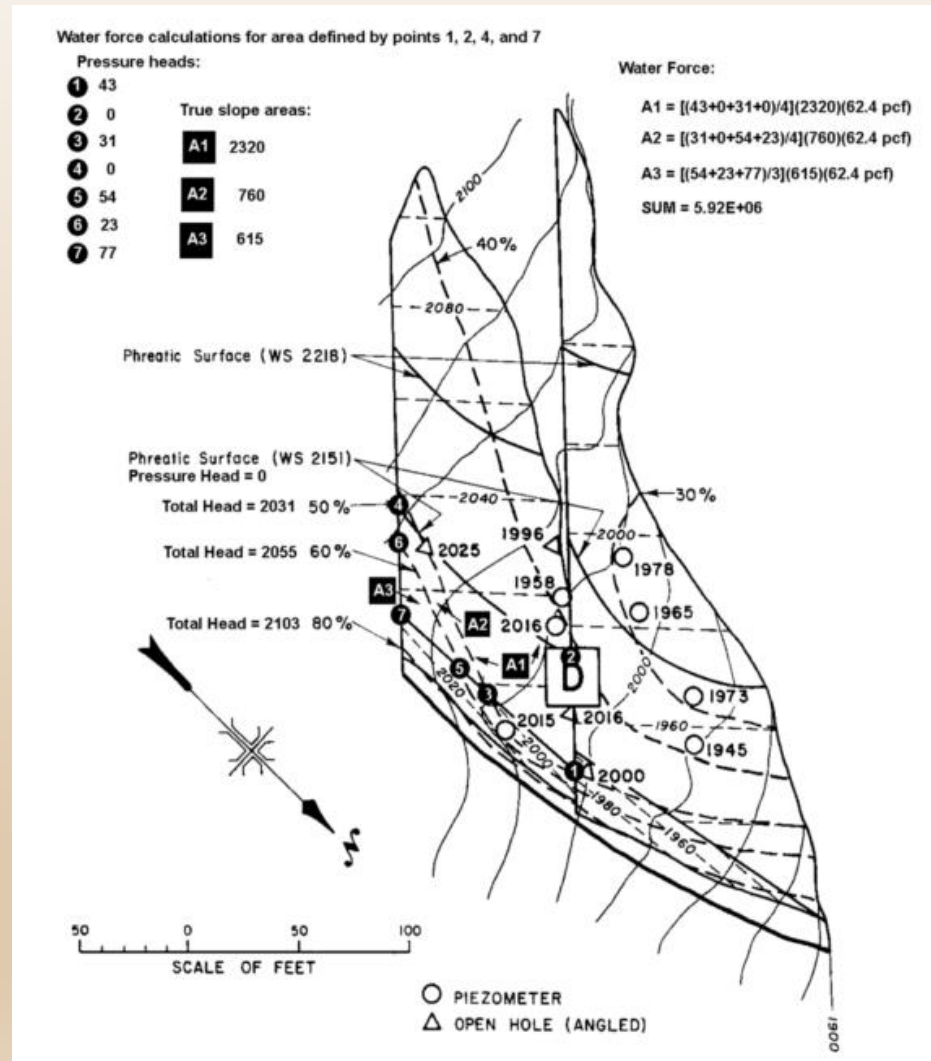
Careful when grouting under reservoir head. Grout may travel downstream and set up, backing up increased pressures upstream under the dam.

If counting on grout curtain cutoff to reduce pressures, must verify with measurements

Arthur Casagrande, 1st Rankine Lecture



Water Forces on Block Planes



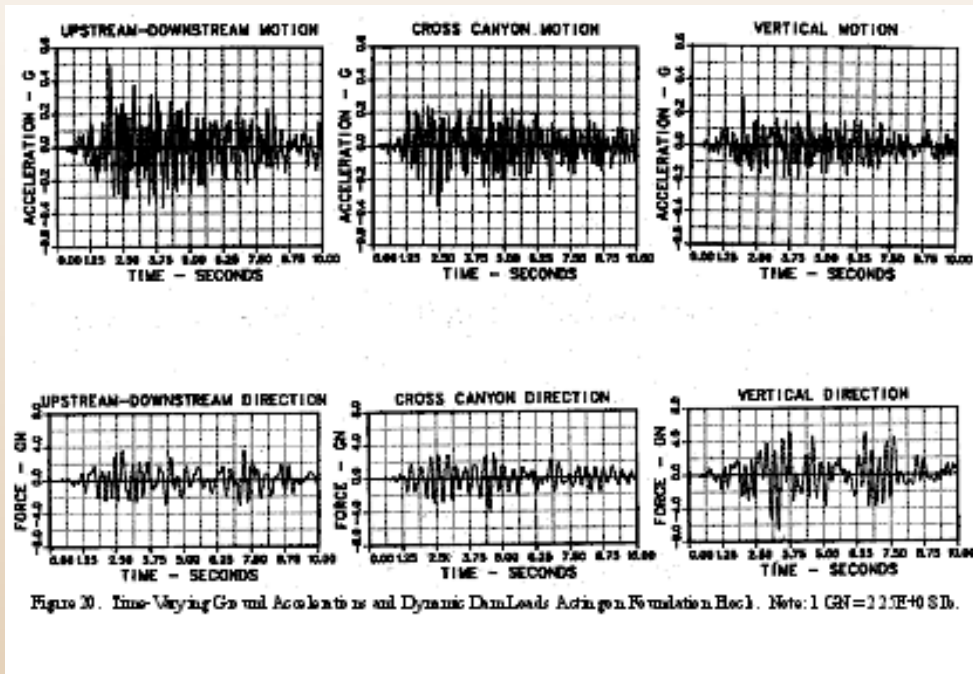
- Determine submerged area for each block plane
- Discretize each plane wetted area
- Calculate force for each area
- Sum to get total force on each plane

Figure 23. Example Water Force Calculation. Note: 1 ft = 0.3048 m, 1pcf = 16 kg/m³, 1 lb = 4.45 N

Dam Loading and Rock Mass Modulus Considerations



Dam Loads and Inertia Loads



For uncoupled analyses

Include static loads

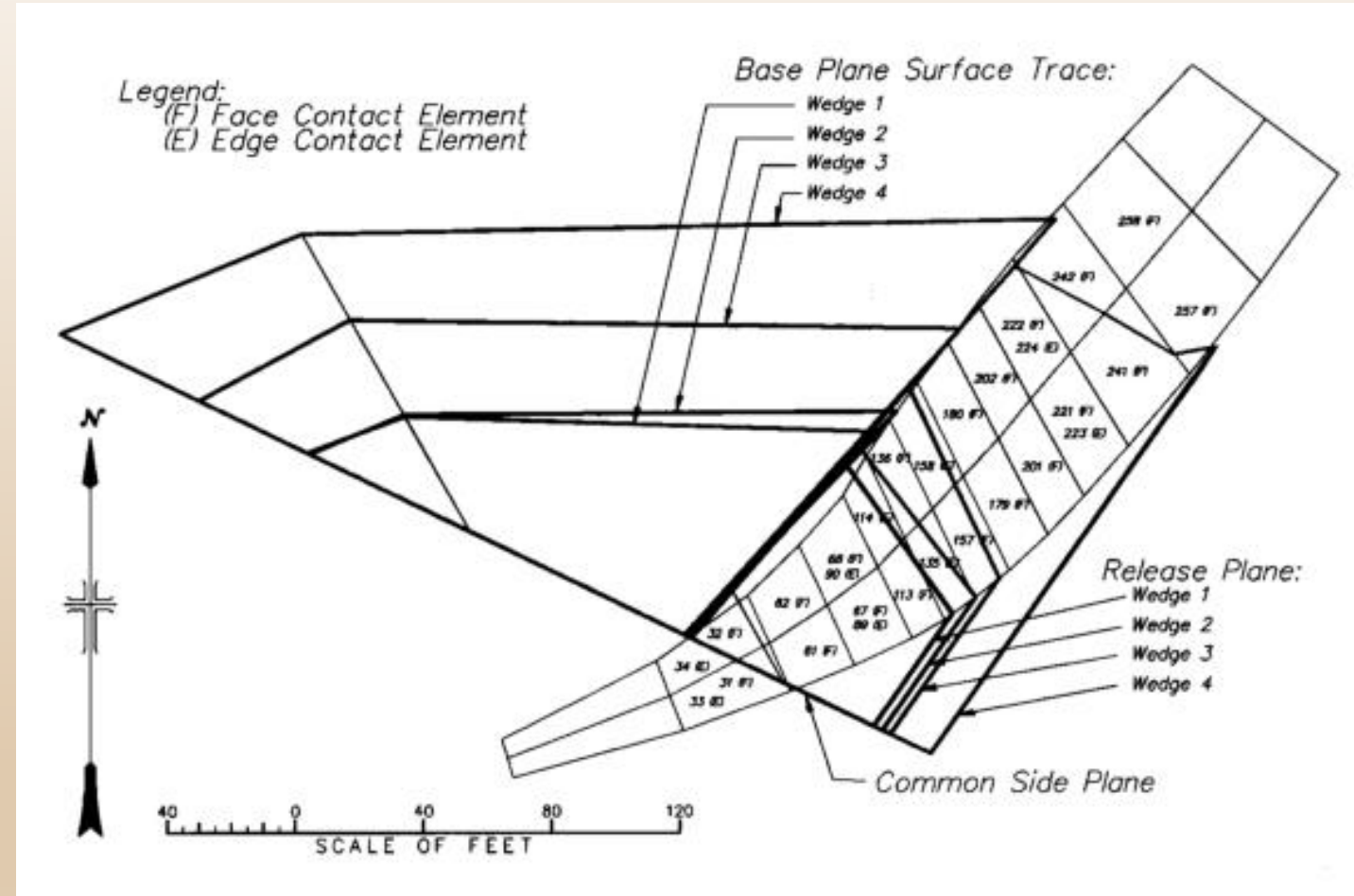


Figure 21. Finite Element Mesh Footprint Shown in Relationship to Foundation Blocks Identified at Morrow Point Dam. Note: 1 ft = 0.3048 m.

Foundation Rock Mass Modulus

- Affects load distribution, is critical to calculating dam loading
- Is not the intact laboratory modulus – affected by discontinuities
- Is probably not the geophysical modulus – strain too small
- Foundation modulus can be determined from empirical relationships, in-situ testing, or calibration to measured deformations or shake test frequencies
- In two cases where jacking tests were performed before and after grouting (Davis Dam and Auburn Dam) there was virtually no change in the rock mass modulus – no increase from grouting

Foundation Rock Mass Modulus (cont.)

- Too small of a foundation modulus can over-dampen the system for dynamic calculations (i.e. low value is not conservative)
Calibration to shake tests useful.
- Typically, stiffer foundation modulus values are more conservative relative to structural response and loading as shown in table below
- But, should perform sensitivity studies to see what the difference is with respect to foundation load and stress distribution

Modulus Case	Factor of Safety		
	Block D Left Abutment	Block E Channel Area	Block F Right Abutment
Case 1 (Soft)	2.8	2.1	3.2
Case 2 (Stiff)	2.1	1.9	2.3



Multi-Block Systems



Multi-Block Foundation Systems

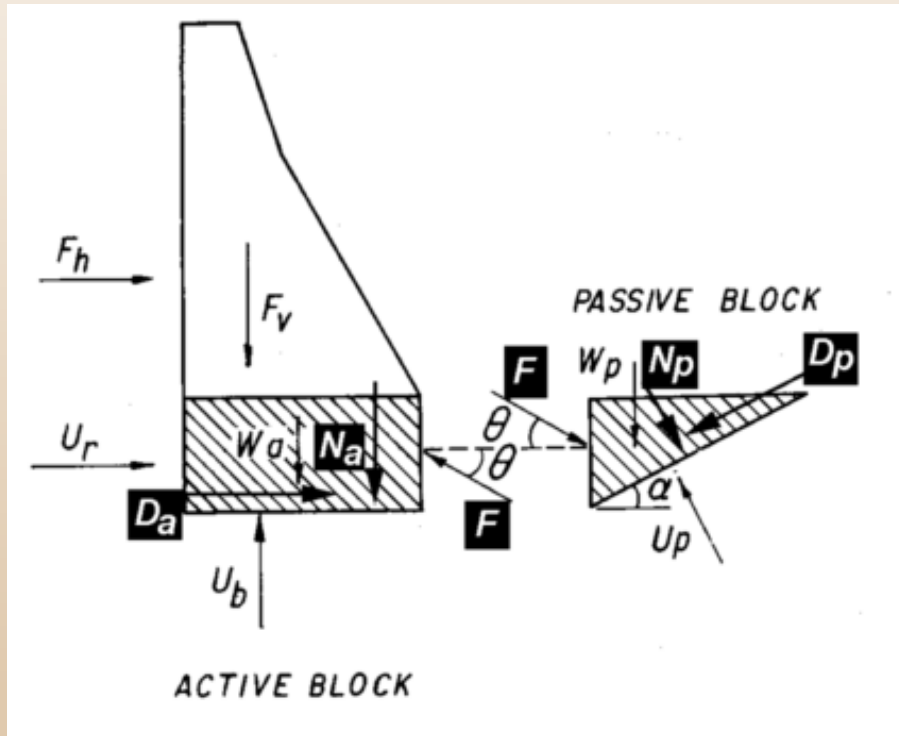
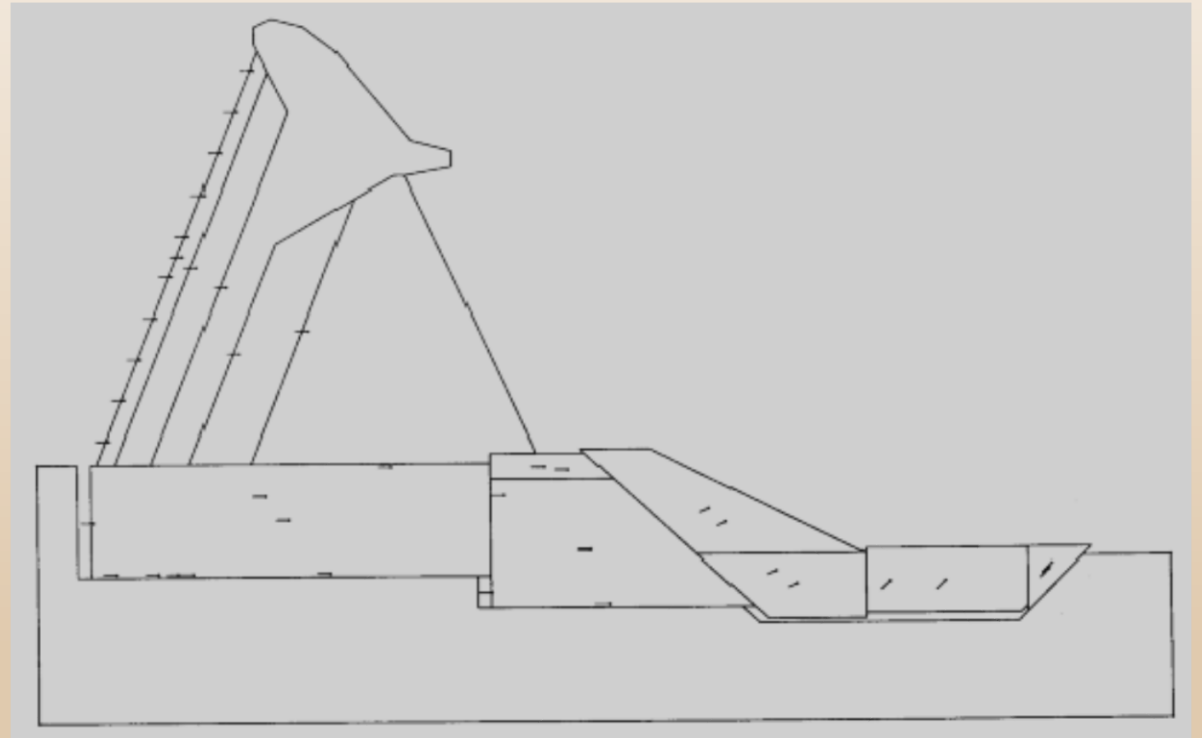


Figure E1. Forces Acting on Two Block System. Forces in Black Boxes Represent Summation of Forces Resolved into the Shown Directions

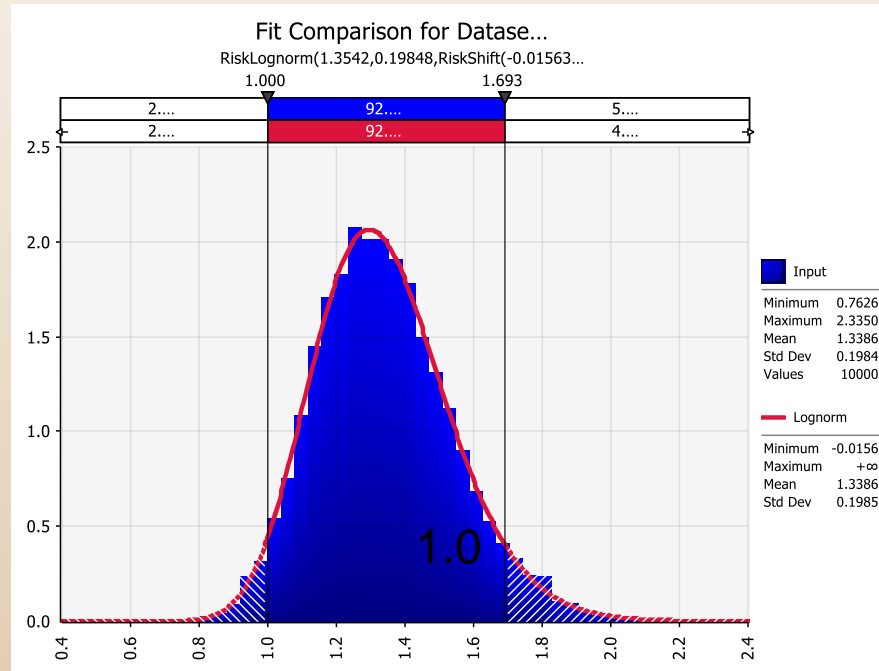
- Unless passive block is very thin, the rock material is weak or there is an adversely oriented discontinuity, shearing through passive rock mass is unlikely
- There must also be shearing along a near vertical feature between blocks
- Results are highly sensitive to assumed interblock force angle theta – approaches friction angle at limit of equilibrium

Distinct Element Analysis

- For multiblock analysis, distinct element or discontinuous deformation analysis (DDA) evaluations are more appropriate – account for interblock forces and their orientations



Sliding Factor of Safety



Results from probabilistic
factor of safety calculations

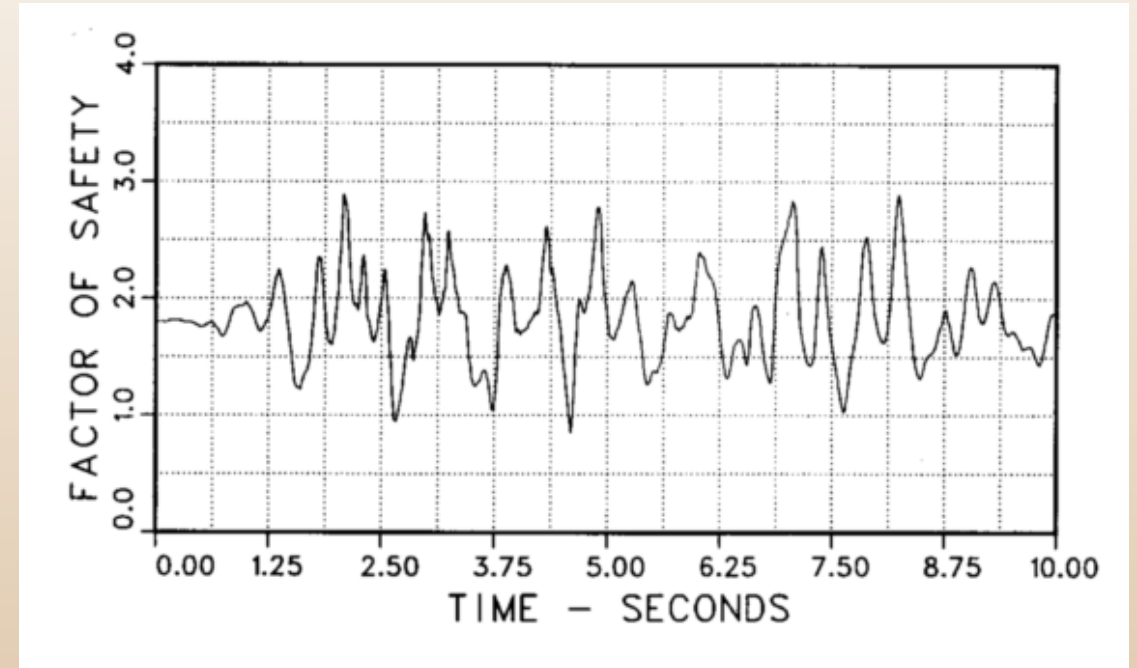
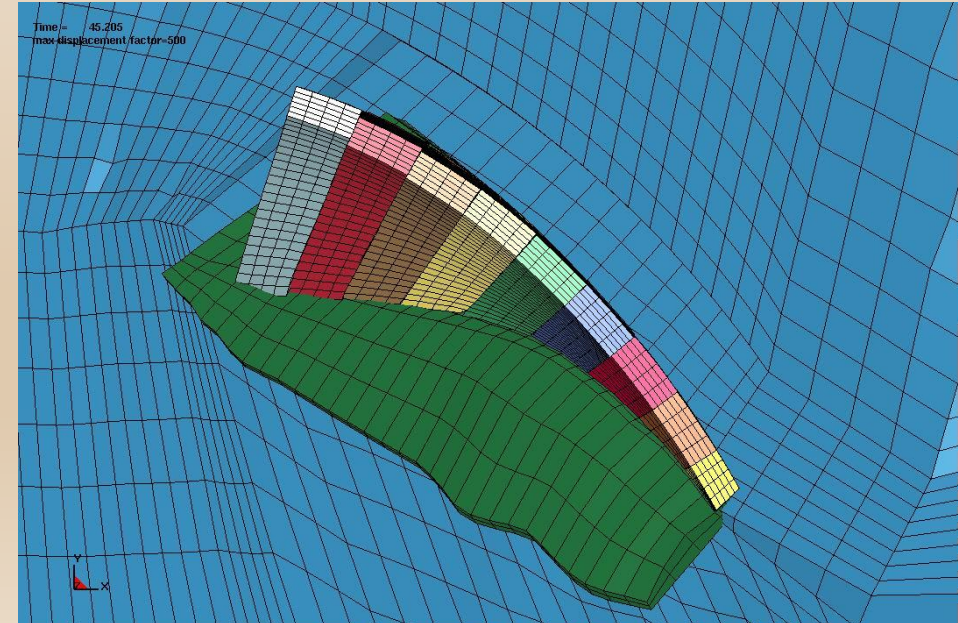
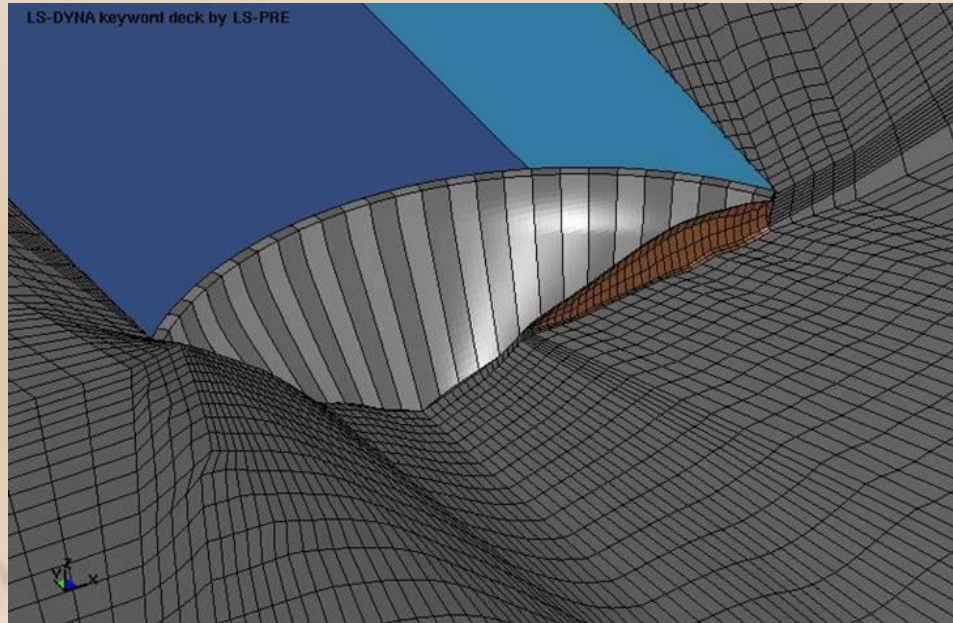


Figure 28. Factor of Safety as a Function of Time for Dynamic Analysis of Foundation Block

“Newmark” displacements when factor of
safety drops below 1.0. Large
displacements would be unrealistically
conservative

Nonlinear Coupled Analysis

- Typically only completed if an uncoupled analysis indicates large displacements and high risks are estimated
- Time consuming and expensive
- Requires thorough exercising and testing to validate the model is behaving properly and the results are reasonable



Takeaway Points

- Foundation deficiencies are the leading cause of concrete dam failures
- Careful evaluation of the 3-D geology and discontinuity geometry is needed to evaluate potential block formation and failure modes
- Analyses need to consider foundation modulus and dam loads, water uplift pressures, and scale-dependent shear strength, along with their variability and uncertainty
- Probabilistic and traditional deterministic stability analyses are needed in most cases
- The exercise that follows is key to understanding how to estimate these risks. An event tree will be developed, which can be used to evaluate potential corrective actions for high risk situations



Questions or Comments?



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